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Specification and Drawings, as originally filed, with Application for Patent Serial No: **2,329,475** on December 11, 2000, by **QUESTAIR TECHNOLOGIES INC.,** assignee of Bowie Keefer, Matthew Babicki, Surajit Roy and Andrea Gibbs, for "Fast Cycle PSA with Adsorbents Sensitive to Atmospheric Humidity ".

Sylvie Grégoire

Agent certificateur/Certifying Officer

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Fast Cycle PSA with Adsorbents Sensitive to Atmospheric Humidity

FIELD OF THE INVENTION

The invention relates to gas separation by pressure swing adsorption processes operating at high frequency with adsorbents which may be sensitive to deactivation by atmospheric humidity. A particular application is oxygen enrichment of air using nitrogen-selective adsorbents which are hydrophilic in their activated condition.

BACKGROUND OF THE INVENTION

Gas separation by pressure swing adsorption is achieved by coordinated pressure cycling and flow reversals over an adsorber that preferentially adsorbs a more readily adsorbed component relative to a less readily adsorbed component of the mixture. The total pressure is elevated during intervals of flow in a first direction through the adsorber from a first end to a second end of the adsorber, and is reduced during intervals of flow in the reverse direction. As the cycle is repeated, the less readily adsorbed component is concentrated in the first direction, while the more readily adsorbed component is concentrated in the reverse direction.

A "light" product, depleted in the more readily adsorbed component and enriched in the less readily adsorbed component, is then delivered from the second end of the adsorber. A "heavy" product enriched in the more strongly adsorbed component is exhausted from the first end of the adsorber. The light product is usually the desired product to be purified, and the heavy product often a waste product, as in the important examples of oxygen separation over nitrogen-selective zeolite adsorbents and hydrogen purification. The heavy product (enriched in nitrogen as the more readily adsorbed component) is a desired product in the example of nitrogen separation over nitrogen-selective zeolite adsorbents. Typically, the feed is admitted to the first end of a adsorber and the light product is delivered from the second end of the adsorber when the pressure in that adsorber is elevated to a higher working pressure. The heavy product is exhausted from the first end of the adsorber at a lower working pressure. In order to achieve high purity of the light product,

a fraction of the light product or gas enriched in the less readily adsorbed component is recycled back to the adsorbers as "light reflux" gas after pressure letdown, e.g. to perform purge, pressure equalization or repressurization steps.

The conventional process for gas separation by pressure swing adsorption uses two or more adsorbers in parallel, with directional valving at each end of each adsorber to connect the adsorbers in alternating sequence to pressure sources and sinks, thus establishing the changes of working pressure and flow direction. The basic pressure swing adsorption process also makes inefficient use of applied energy, because of irreversible expansion over the valves while switching the adsorbers between higher and lower pressures. More sophisticated conventional pressure swing adsorption devices achieve some improvement in efficiency by use of multiple pressure equalization steps and other process refinements, but complexity of the valve logic based on conventional 2-way valves is greatly increased. Furthermore, the cycle frequency with conventional valves and granular adsorbent cannot be greatly increased, so the adsorbent inventory is large. Conventional PSA plants are accordingly bulky and heavy, and there is a need for much more compact PSA technology.

By operating with high surface area laminated adsorbers, with the adsorbent supported in thin sheets separated by spacers to define flow channels between adjacent sheets, and with the adsorbers mounted in a rotor to provide the PSA process valve logic with only one moving part, a high frequency PSA cycle can be performed in an extremely compact apparatus as disclosed by Keefer et al (U.S. Patent No. 6,051,050), the disclosure of which is incorporated herein by reference.

The present invention addresses unexpectedly severe problems with adsorbent deactivation that have been encountered with pressure swing adsorption (PSA) or vacuum pressure swing adsorption (VPSA) gas separation processes using strongly hydrophilic adsorbents and operating at exceptionally high cycle frequency. Such deactivation problems are severe in PSA or VPSA processes working with atmospheric air feed of any normal humidity, and are particularly

severe with the highest performance nitrogen-selective adsorbents widely used for oxygen enrichment. Hydrophilic adsorbents such as Li or Ca exchanged low silica X zeolites are extremely sensitive to deactivation by adsorbed water. This problem is most severe in applications with intermittent operation and/or extended shutdowns.

Conventional industrial PSA and VPSA systems operate at low cycle frequency with large inventories of adsorbent, and are relatively insensitive to minor contamination by atmospheric humidity because of (1) the relatively large dimension of the adsorbers across which humidity diffusion may take place, (2) the slow rate of any deterioration dependant on the cumulative number of cycles experienced, and (3) the relative insensitivity to deactivation of a small fraction of a large adsorbent inventory. Hence, a conventional system may operate for many years with no noticeable degradation.

The inventors have developed advanced PSA or VPSA systems whose operating frequency is some two orders of magnitude faster than conventional industrial PSA processes. Consequently the adsorbent inventory is smaller by approximately the same factor of two orders of magnitude, and the dimension of the adsorbers across which humidity diffusion may take place is also reduced by a large factor.

The inventors have found experimentally that a serious performance decline takes place owing to adsorbent deactivation by water adsorption, within about two months while operating continuously with water saturated air feed at cycle frequencies of the order of 60 cycles/minute, unless the inventive devices and procedures the present invention are applied to prevent such rapid decline. The performance decline is indicated by a loss of productivity and product yield while operating to maintain delivered oxygen product purity at fixed cycle frequency and within a fixed working pressure range. The tests were conducted using a lithium exchanged low silica X zeolite adsorbent.

The inventors have determined solutions for water management challenges that arise in the operation of fast cycle PSA equipment in normal continuous operation, and have further addressed the more serious challenges that arise under intermittent operation of PSA equipment under diverse climatic conditions of ambient temperature and humidity. When a PSA unit is shutdown, any adsorbed water in any part of the adsorber may diffuse detrimentally into water-sensitive zones of activated adsorbent to cause deactivation. Furthermore, normal fluctuations of ambient temperature and barometric pressure may cause an idled PSA unit to take in humid air through any breather port or through leakage paths in imperfectly closed valves, seals, and compression machinery. Hence, the invention also addresses humidity-safe shutdown procedures, and supplementary devices for excluding or minimizing humidity ingress into a fast cycle PSA unit when it is in a storage, idled or "parked" condition.

SUMMARY OF THE INVENTION

Aspects of the invention are discussed under the headings of normal operation, shutdown procedures, and parked condition of the PSA unit with water-sensitive adsorbent.

Normal Operation

In normal operation of conventional PSA units, water transport from humid feed entering the feed end is prevented by any of the following measures: (1) using a feed air dryer upstream of the PSA unit, (2) using a desiccant layer at the feed end of the adsorbers, and (3) allowing a "sacrificial" layer of the water-sensitive adsorbent adjacent the feed end of the adsorbers to deactivate while functioning effectively as a desiccant.

In preferred embodiments of the present invention, the adsorbers are provided as high surface area laminated adsorbers, with the adsorbent supported in

thin adsorbent sheets separated by spacers to define flow channels between adjacent sheets. A desiccant strip is provided at the feed end of the adsorbent sheets, by coating the leading edge of the sheets with a suitable desiccant such as alumina. Alternatively, a narrow ribbon coated with alumina may be placed on the feed side of an adsorbent sheet coated with the water –sensitive adsorbent.

Ideally, we want a desiccant which adsorbs water strongly (so that the strip is short) but with a water isotherm that is reasonably linear (easy regeneration, smallest possible adsorbed water inventory) over the working range. We may want to select an adsorbent with "best" properties for PSA operation, but also "good" properties for thermal swing regeneration to knock out the adsorbed water inventory as a shutdown procedure. The design must determine required width of strip, steady state accumulated adsorbed water profile, effective diffusion rate and ease of regeneration for alternative desiccants.

In order to prevent humidity bypass of the desiccant, it is important to minimize leakage past laminate packs, static seals, and any gross channeling. Static seal configurations and compounds must be selected for low water permeation flux.

Water leakage into product valve and lines must stringently be avoided since humidity contaminating the product end of the adsorbers will work backwards under operation of the PSA process to degrade the entire adsorbent inventory eventually. The object is to prevent water ingress into the product end of the adsorbers from all pathways. Hence, careful precautions must be taken to minimize boundary layer back-diffusion and surface diffusion from downstream product lines, valves and receivers; and to have absolutely tight shut-off valves to close the product delivery line when the unit is shut down.

The directional control valves that execute the PSA cycle at the product ends of the adsorbers (here, preferably rotary multiport distributor valves) must be designed so that leakage of humid air into these valves and thence into the

adsorbers is strictly avoided. Such leakage is more likely when the PSA beds are vacuum regenerated as in normal practice. Humidity leakage prevention is especially difficult for the circumferential seals of relatively large diameter rotary multiport distributor valves, although actuator packings of any type of directional valve will also provide potential leakage pathways for humidity ingress. The approach provided within the present invention is to provide a buffer space between the internal working zone of valves communicating to the product ends of the adsorbers. The buffer space is a positive pressured dry oxygen flushed zone, with flushing circulation conveniently by delivered product flow. For rotary multiport distributor valves, the buffer space is defined by a buffer seal, preferably of much smaller diameter than the circumferential seals or sealing face of the rotary valve.

The invention provides desiccant traps in all light reflux lines (and the buffer space of any directional valve) to capture any mobile water, particularly upon initial startup or upon startup after any maintenance intervention which may have introduced humid air into the PSA unit. The activity of such desiccant traps may be maintained by periodic regeneration or replacement. The desiccant traps in light reflux lines may serve usefully as surge absorber chambers or equalization buffer tanks. These desiccant traps may be static (with periodic replacement or reactivation if needed during scheduled maintenance). The chosen desiccant should be strong, e.g. perhaps used nitrogen-selective adsorbent.

If one of these desiccant traps is in the product line, its steady state humidity level corresponds to that of the dry delivered product. If a previously water loaded desiccant trap is valved into the product line, it will be gradually regenerated to a high degree by displacement purge of product gas. An auxiliary valving arrangement may be used to rotate desiccant traps between the light reflux lines and the product line, for displacement purged regeneration by the product. The dry product may also be used to regenerate any auxiliary beds used as (1) a humidity sink for regenerating desiccant at the front end of the adsorbers, or (2) isolation desiccant traps for air breather lines when the unit is in shutdown mode.

Shutdown Procedures

Forward diffusion of water from previously adsorbed in the feed end desiccant strip of the adsorbers is a serious hazard for progressive deactivation of the water-sensitive adsorbent whenever the PSA unit is shut down. Alternative approaches within the invention include (1) isolation valves, (2) back purge with dry product, (3) back purge with auxiliary heating of the desiccant strip, and (4) recirculated back purge to transfer humidity from the desiccant strip to an auxiliary desiccant bed.

Isolation valves may be provided between desiccant and the water-sensitive adsorbent zones in each adsorber. These valves are open whenever the unit is operating, but are closed automatically whenever the unit stops. The isolation valves may be normally closed, and then opened either by admission of feed pressurized above ambient or by rotation of the rotary PSA module of preferred embodiments. The isolation valves must close tightly to withstand pressure fluctuations due to ambient temperature variations, to avoid forcing ambient humidity ingress into the adsorbers.

Particularly preferred strategies entail regeneration of the desiccant strip to eliminate most of the adsorbed water in the desiccant. With high concentrations of adsorbed water, water diffuses relatively rapidly because the slope of the water isotherm is less steep. When nearly all of the water has been removed by successful regeneration, water diffuses much more slowly because the slope of the water isotherm is extremely steep. Hence, the rate of deactivation of our water-sensitive adsorbent can be greatly reduced by nearly complete regeneration of the desiccant; and a substantial improvement can be obtained by only partial regeneration of the desiccant to remove the excess water which has greatest diffusive mobility.

Initial desiccant regeneration can be achieved by an automatic back purge with stored dry oxygen product upon shutdown. To ensure equal regeneration of the desiccant strip in all adsorbers, it is important to keep the rotor turning during purge. As a very large volume of stored dry product would be required to achieve substantially complete regeneration of the desiccant strip, the effectiveness of regeneration may be enhanced by back purging with the assistance of the operating vacuum pump.

A greater enhancement of desiccant regeneration may be achieved by auxiliary heating of the desiccant strip during the shutdown procedure and while back purging is underway with or without vaccum assist. Alternative heat sources auxiliary resistance heaters, inductive eddy current heating (e.g. of a metallic mesh or foil in the adsorbent sheets) or microwave radiation. Alternatively, heat may be provided to the desiccant strip by deliberately increased heating (or reduced normal cooling) by the vacuum pump and compressor operating with recirculating gas flows, or by rotary valve seal friction which may be increased by increasing valve face mechanical loading.

Even with vacuum assist and auxiliary heating of the desiccant strip, the volume of dry product required for back purging may be unreasonably large. Hence, another aspect of the invention is to extend back purge by using the vacuum pump for recirculated purge by product gas through an auxiliary desiccant/adsorbent bed, which will be regenerated in normal operation by dry product flow through that adsorbent bed and/or by thermal swing heating.

Again, the shutdown procedure must be designed to place the PSA unit in a humidity-safe parked condition under which water leakage into the product end of the adsorbers is strictly prevented by appropriate tightly closed shut-off valves and/or non-return valves. Water ingress into the product ends of the adsorbers must be stopped from any and all pathways. Tight sealing of buffer seals around circumferential rotary valve seals or valve actuator stems may be augmented by automatically engaged parking seal(s). During normal operation of a rotary PSA

embodiment, the buffer seal should be designed for low friction and long life. Its sealing tightness during operation may be non-critical since the buffer chamber is then positively pressurized above ambient pressure. Sealing tightness does become critical during shutdown, as any direct "breathing" of humid ambient air into the product ends of the adsorbers must be strictly prevented. The buffer seal may therefore be supplemented by a "parking seal", which enters a tightly closed engagement automatically when either (1) rotation of a rotary PSA module is discontinued, or alternatively when (2) the PSA unit is unpressurized owing to discontinuation of compressed feed gas supply.

Parked Condition

As described above, a proper shutdown procedure will have protected the water-sensitive adsorbent zones from deactivation, either by engaging isolation valves to isolate the water containing desiccant strip, or else by regenerating the desiccant strip.

When the PSA unit has been shutdown, it is externally exposed to humid air, and it is subjected to normal fluctuations of diurnal temperature and barometric pressure. As indicated above, it is mandatory that water transport from humid air breathing in and out of the product end of the PSA unit be substantially completely excluded. The invention next addresses the issue of preventing or managing humid air breathing in and out of the feed end of the PSA unit.

In one aspect of the invention with several embodiments, the water-sensitive zone of the PSA unit is totally or at least partially sealed on shutdown. In a completely sealed shutdown, the PSA unit (or its water-sensitive zone) is tightly sealed on all ports after shutdown. As the unit cools from its normal operating temperature (here assumed to be somewhat above normal ambient temperature), it pulls a strong vacuum which may be further enhanced while adsorbed nitrogen redistributes by diffusion. A relief valve is provided to vent

any excess air if the pressure starts cycling up to higher pressures as a result of any slow leakage inward, or as a result of inadvertent heating of the unit. Similarly, a relief valve may be provided to permit a modest inflow of air to the feed end of the PSA unit as may be required to relieve excessive differential pressure between external ambient pressure and the internal vacuum pressure.

In another aspect of the invention, the PSA unit is tightly sealed on all product end ports and seals, but is only partially sealed sealed on feed ports so as to allow restricted breathing in response to changes of ambient temperature and barometric pressure. Crossover relief valves with a low cracking pressure setting may be provided to permit limited feed end breathing only as required to prevent excessive over-pressure or vacuum differentials that would overload the unit structurally or cause some risk that breathing of humid air into the product end may take place despite all precautions. Any breathing of external air into the feed end of the PSA unit would be through the desiccant strip at the feed end of adsorbers. An extra air breather desiccant bed may be provided on an air breather port communicating to the feed end of the PSA unit.

A further refinement of the invention is thermal design of air breather and air breather desiccant bed in conjunction with the PSA module, so that ambient temperature swings penetrate the desiccant bed associated with the air breather very rapidly and penetrate the the PSA module more slowly. Hence a phase shift is established between temperature swings in the air breather desiccant bed and air flows through that desiccant bed, as those air flows will be in phase with the rate of delayed temperature change within the adsorbers of the PSA unit. Air flow into the PSA unit occurs as it is cooling down, after the air breather desiccant bed has already cooled down so as to adsorb humidity more strongly. Air flow out of the PSA unit occurs as it is warming up, after the air breather desiccant bed has already warmed up so as to release adsorbed water vapour.

Consequently a thermal swing adsorption (TSA) process is established in the air breather desiccant bed, operative to slowly expel water out of the PSA unit

on a 24 hour nominal cycle. This auxiliary TSA humidity expulsion process could have passive solar augmentation for extra thermal swing. The air breather desiccant bed may be designed with a large volume and a long flow path to minimize the rate of nitrogen mixing into oxygen within the adsorbers.

Another aspect of the invention more simply is to provide the air breather as a long tube (with or without desiccant) to retard bulk mixing of humid external air with dry oxygen in the adsorbers. Otherwise, air breathing will result in nitrogen uptake with a net inward flow of several bed volumes into the adsorbers, plus pumping of feed end humidity.
Tests of this embodiment have established that the rate of adsorbent deactivation under air breathing (as forced by cyclic ambient temperature variations) is greatly retarded by an air breather tube whose internal volume may be much less than the adsorber volume.

Yet another aspect of the invention is to provide an air breather as an inflated bag diaphragm approximately equilibriated with ambient pressure, to prevent bulk mixing of humid external air with dry oxygen within the adsorbers.

As mentioned above, water ingress during shutdown may be prevented by tight shut-off valves or non-return valves in downstream product lines, and by parking seals around circumferential dynamic seals of rotary valves and any valve actuator stems. Parking seals should be extremely tight, and on a small diameter by good mechanical design. Desiccant traps in light reflux lines and valve buffer spaces can capture any mobile water, with periodic regeneration or replacement of those desiccant traps being included in normal PSA unit maintenance procedures..

It is important to avoid non-uniform adsorber degradation owing to parked position of valve ports singling out particular adsorbers to get different shutdown circulation patterns and humidity exposure. This risk ma be addressed by any of the following measures:

(1) remove water very stringently upon shutdown, and then seal tightly, (2) periodically turn rotor during shutdown, or (3) lift valve face(s) off seat during shutdown so that all adsorbers are vented together.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows an axial section of a rotary PSA module.

Figs. 2 through 5B show transverse sections of the module of Fig. 1.

Figs. 6 through 15 show a simplified and generalized schematic of fast cycle PSA modules with devices for preventing or inhibiting deactivation of the water-sensitive adsorbent zone.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figs. 1 - 5

Fig. 1 shows a rotary PSA module 1, particularly suitable for smaller scale oxygen generation. Module 1 includes a number "N" of adsorbers 3 in adsorber housing body 4.

Each adsorber has a first end 5 and a second end 6, with a flow path therebetween contacting a nitrogen-selective adsorbent. Each adsorber has a first zone 3A adjacent its first end, and a second zone 3B extending to the second end. First zone 3A contains a desiccant such as activated alumina or a zeolite adsorbent, and second zone 3B contains a water-sensitive nitrogen-selective adsorbent as further described below. Typically, zone 3A extends over about 15% of the adsorber length between the first and second ends, and zone 3B (which may in turn be subdivided into a plurality of zones containing different adsorbents) is the remaining 85%. The adsorbers are deployed in an axisymmetric array about axis 7 of the adsorber housing body. The housing body 4 is in relative rotary

motion about axis 7 with first and second valve bodies 8 and 9, housing body 4 being engaged across a first valve face 10 with the first valve body 8 to which feed air is supplied and from which nitrogen-enriched air is withdrawn as the heavy product, and housing body 4 being engaged across a second valve face 11 with the second valve body 9 from which oxygen-enriched air is withdrawn as the light product.

In some embodiments (not shown), the adsorber housing body may be stationary, while the first and second valve bodies rotate. In those preferred embodiments as particularly depicted in Figs. 1 - 5, the adsorber housing 4 rotates and shall henceforth be referred to as the adsorber rotor 4, while the first and second valve bodies are stationary and together constitute a stator assembly 12 of the module. The first valve body shall henceforth be referred to as the first valve stator 8, and the second valve body shall henceforth be referred to as the second valve stator 9.

In the embodiment shown in Figs. 1 - 5, the flow path through the adsorbers is parallel to axis 7, so that the flow direction is axial, while the first and second valve faces are shown as flat annular discs normal to axis 7. However, more generally the flow direction in the adsorbers may be axial or radial, and the first and second valve faces may be any figure of revolution centred on axis 7. The steps of the process and the functional compartments to be defined will be in the same angular relationship regardless of a radial or axial flow direction in the adsorbers.

Figs. 2 - 5 are cross sections of module 1 in the planes defined by arrows 12 - 13, 14 - 15, and 16 - 17. Arrow 20 in each section shows the direction of rotation of the rotor 4.

Fig. 2 shows section 12 - 13 across Fig.1, which crosses the adsorber rotor. Here, "N" = 72. The adsorbers 3 are mounted between outer wall 21 and inner wall 22 of adsorber wheel 208. Each adsorber comprises a rectangular

flat pack 3 of adsorbent sheets 23, with spacers 24 between the sheets to define flow channels here in the axial direction. Separators 25 are provided between the adsorbers to fill void space and prevent leakage between the adsorbers.

The adsorbent sheets comprise a reinforcement material, in preferred embodiments glass fibre, metal foil or wire mesh, to which the adsorbent material is attached with a suitable binder. For air separation to produce enriched oxygen, typical adsorbents in second zone 3B are X, A or chabazite type zeolites, typically exchanged with lithium, calcium, strontium, magnesium and/or other cations, and with optimized silicon/aluminum ratios as well known in the art. The zeolite crystals are bound with silica, clay and other binders, or self-bound, within the adsorbent sheet matrix.

Satisfactory adsorbent sheets have been made by coating a slurry of zeolite crystals with binder constituents onto the reinforcement material, with successful examples including nonwoven fibreglass scrims, woven metal fabrics, and expanded aluminum foils. Spacers are provided by printing or embossing the adsorbent sheet with a raised pattern, or by placing a fabricated spacer between adjacent pairs of adsorbent sheets. Alternative satisfactory spacers have been provided as woven metal screens, non-woven fibreglass scrims, and metal foils with etched flow channels in a photolithographic pattern.

Typical experimental sheet thicknesses have been 150 microns, with spacer heights in the range of 100 to 150 microns, and adsorber flow channel length approximately 20 cm. Using X type zeolites, excellent performance has been achieved in oxygen separation from air at PSA cycle frequencies in the range of 30 to 150 cycles per minute.

Fig. 3 shows the porting of rotor 4 in the first and second valve faces respectively in the planes defined by arrows 14 - 15, and 16 - 17. An adsorber port 30 provides fluid communication directly from the first or second end of each adsorber to respectively the first or second valve face.

Fig. 4 shows the first stator valve face 100 of the first stator 8 in the first valve face 10, in the plane defined by arrows 14 – 15. Fluid connections are shown to a feed compressor 101 inducting feed air from inlet filter 102, and to an exhauster 103 delivering nitrogen-enriched second product to a second product delivery conduit 104. Compressor 101 and exhauster 103 are shown coupled to a drive motor 105.

Arrow 20 indicates the direction of rotation by the adsorber rotor. In the annular valve face between circumferential seals 106 and 107, the open area of first stator valve face 100 ported to the feed and exhaust compartments is indicated by clear angular segments 111 - 116 corresponding to the first functional ports communicating directly to functional compartments identified by the same reference numerals 111 - 116. The substantially closed area of valve face 100 between functional compartments is indicated by hatched sectors 118 and 119 which are slippers with zero clearance, or preferably a narrow clearance to reduce friction and wear without excessive leakage. Typical closed sector 118 provides a transition for an adsorber, between being open to compartment 114 and open to compartment 115. Gradual opening is provided by a tapering clearance channel between the slipper and the sealing face, so as to achieve gentle pressure equalization of an adsorber being opened to a new compartment. Much wider closed sectors (e.g. 119) are provided to substantially close flow to or from one end of the adsorbers when pressurization or blowdown is being performed from the other end.

The feed compressor provides feed air to feed pressurization compartments 111 and 112, and to feed production compartment 113. Compartments 111 and 112 have succcessively increasing working pressures, while compartment 113 is at the higher working pressure of the PSA cycle. Compressor 101 may thus be a multistage or split stream compressor system delivering the appropriate volume of feed flow to each compartment so as to achieve the pressurization of adsorbers through the intermediate pressure levels of compartments 111 and 112, and then the final pressurization and production through compartment 113. A split stream compressor system may be provided in series as a multistage compressor with

interstage delivery ports; or as a plurality of compressors or compression cylinders in parallel, each delivering feed air to the working pressure of a compartment 111 to 113. Alternatively, compressor 101 may deliver all the feed air to the higher pressure, with throttling of some of that air to supply feed pressurization compartments 111 and 112 at their respective intermediate pressures.

Similar, exhauster 103 exhausts nitrogen-enriched heavy product gas from countercurrent blowdown compartments 114 and 115 at the successively decreasing working pressures of those compartments, and finally from exhaust compartment 116 which is at the lower pressure of the cycle. Similarly to compressor 101, exhauster 103 may be provided as a multistage or split stream machine, with stages in series or in parallel to accept each flow at the appropriate intermediate pressure descending to the lower pressure.

In the example embodiment of Fig. 4A, the lower pressure is ambient pressure, so exhaust compartment 116 exhaust directly to heavy product delivery conduit 104. Exhauster 103 thus provides pressure letdown with energy recovery to assist motor 105 from the countercurrrent blowdown compartments 114 and 115. For simplicity, exhauster 103 may be replaced by throttling orifices as countercurrent blowdown pressure letdown means from compartments 114 and 115.

In some preferred embodiments, the lower pressure of the PSA cycle is subatmospheric. Exhauster 103 is then provided as a vacuum pump, as shown in Fig. 4B. Again, the vacuum pump may be multistage or split stream, with separate stages in series or in parallel, to accept countercurrent blowdown streams exiting their compartments at working pressures greater than the lower pressure which is the deepest vacuum pressure. In Fig. 4B, the early countercurrent blowdown stream from compartment 114 is released at ambient pressure directly to heavy product delivery conduit 104. If for simplicity a single stage vacuum pump were used, the countercurrent blowdown stream from compartment 115 would be throttled down to the lower pressure over an orifice to join the stream from compartment 116 at the inlet of the vacuum pump.

Figs. 5A and 5B shows the second stator valve face, at section 16 - 17 of Fig. 1. Open ports of the valve face are second valve function ports communicating directly to a light product delivery compartment 121; a number of light reflux exit compartments 122, 123, 124 and 125; and the same number of light reflux return compartments 126, 127, 128 and 129 within the second stator. The second valve function ports are in the annular ring defined by circumferential seals 131 and 132. Each pair of light reflux exit and return compartments provides a stage of light reflux pressure letdown, respectively for the PSA process functions of supply to backfill, full or partial pressure equalization, and cocurrent blowdown to purge.

Illustrating the option of light reflux pressure letdown with energy recovery, a split stream light reflux expander 140 is provided to provide pressure let-down of four light reflux stages with energy recovery. The light reflux expander serves as pressure let-down means for each of four light reflux stages, each stage having a light reflux loop conduit 134 respectively between light reflux exit and return compartments 122 and 129, 123 and 128, 124 and 127, and 125 and 126 as illustrated. Desiccant traps (auxiliary desiccant beds) 135 and 136 are respectively installed within the light product delivery conduit 147 and each light reflux loop conduit 134.

Light reflux expander 140 is coupled to a light product pressure booster compressor 145 by drive shaft 146. Compressor 145 receives the light product from conduit 25, and delivers light product (compressed to a delivery pressure above the higher pressure of the PSA cycle) to delivery conduit 147. Since the light reflux and light product are both enriched oxygen streams of approximately the same purity, expander 140 and light product compressor 145 may be hermetically enclosed in a single housing which may conveniently be integrated with the second stator as shown in Fig. 1. This configuration of a "turbocompressor" oxygen booster without a separate drive motor is advantageous, as a useful pressure boost of the product oxygen can be achieved without an external motor and corresponding shaft seals, and can also be very compact when designed to operate at very high shaft speeds.

Fig. 5B shows the simpler alternative of using a throttle orifice 150 as the pressure letdown means for each of the light reflux stages.

Turning back to Fig. 1, compressed feed air is supplied to compartment 113 as indicated by arrow 125, while nitrogen enriched heavy product is exhausted from compartment 117 as indicated by arrow 126. The rotor is supported by bearing 160 with shaft seal 161 on rotor drive shaft 162 in the first stator 8, which is integrally assembled with the first and second valve stators. The adsorber rotor is driven by motor 163 as rotor drive means.

As leakage across outer circumferential seal 131 on the second valve face 11 may compromise enriched oxygen purity, and more importantly may allow ingress of atmospheric humidity into the second ends of the adsorbers which could deactivate the nitrogen-selective adsorbent, a buffer seal 170 is provided to provide more positive sealing of a buffer chamber 171 between seals 131 and 171. Even though the working pressure in some zones of the second valve face may be subatmospheric (in the case that a vacuum pump is used as exhauster 103), buffer chamber is filled with dry enriched oxygen product at a buffer pressure positively above ambient pressure. Hence, minor leakage of dry oxygen outward may take place, but humid air may not leak into the buffer chamber. In order to further minimize leakage and to reduce seal frictional torque, buffer seal 171 seals on a sealing face 172 at a much smaller diameter than the diameter of circumferential seal 131. Buffer seal 170 seals between a rotor extension 175 of adsorber rotor 4 and the sealing face 172 on the second valve stator 9, with rotor extension 175 enveloping the rear portion of second valve stator 9 to form buffer chamber 171. The buffer seal may be designed to have relatively light engagement for low friction and wear while the PSA unit is under normal operating conditions of rotation and pressurization, and then to engage tightly on its sealing face as a "parking" seal when the PSA unit is shut down. The parking seal may also be provided as a separate sealing element cooperating with buffer seal 171, and engaged only during shut down.

Product oxygen from light product functional compartment 121 is delivered by channel 176 into buffer chamber 171, and after circulation through chamber 171 is delivered by conduit 177 to product booster compressor 145 or else directly to product delivery conduit 147. A stator housing member 180 is provided as structural connection between first valve stator 8 and second valve stator 9.

Figs. 6 - 15

In the following figures of this disclosure, simplified schematics will represent the PSA apparatus as described above. These highly simplified drawings will indicate just a single feed conduit 181 to, and a single heavy product conduit 182 from, the first valve face 10; and the light product delivery conduit 147 and a single representative light reflux stage 184 with pressure let-down means communicating to the second valve face 11. Figures 6 – 15 may be taken to include PSA embodiments with rotary adsorbers, PSA embodiments with rotary distributor valves and stationary adsorbers, and for greatest generality other PSA devices with any type of directional valve mechanism and any number of stationary or moving adsorbers.

The adsorbers 3 are contained within an adsorber compartment 200 (shown by dashed lines in Figs. 6 - 15) whose thermal regime is important in some of the embodiments disclosed hereunder. Adsorber compartment 200 may also enclose some or all of the PSA process valving and process logic. Compartment 200 may be simply an area under a given thermal regime isolated from the external ambient to some extent, or it may be physically contained to provide isolation from the external humid atmosphere as a general approach to protect the PSA system against water vapour ingress by any pathway.

The following embodiments provide solutions for humidity management with water-sensitive adsorbents under normal operation, shutdown procedures and parked condition of the PSA unit. While the discussion will focus on the important application to oxygen enrichment over nitrogen-selective adsorbents which are especially water-sensitive, it will be appreciated that the features of the

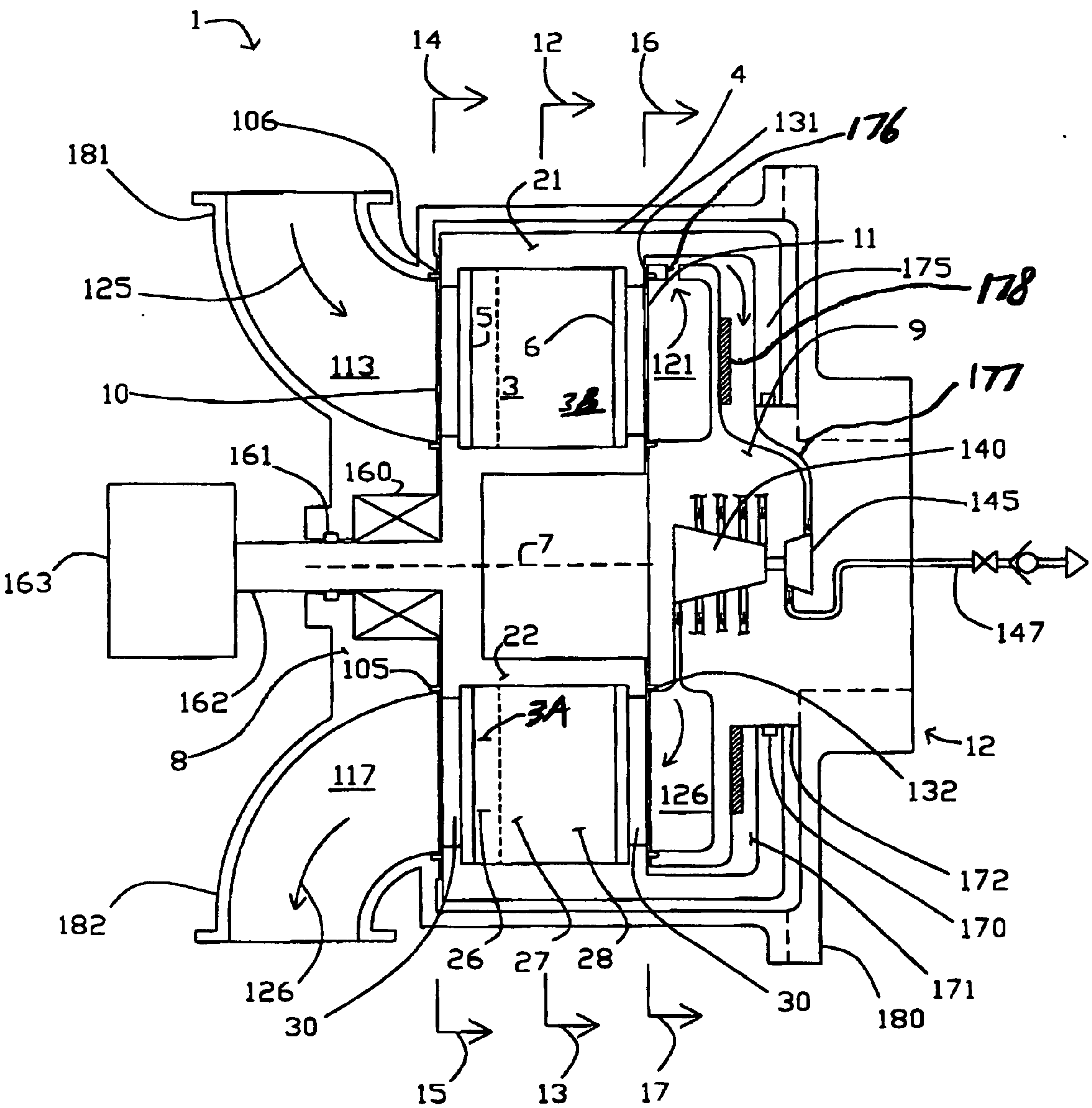
invention are broadly applicable to any PSA device and process for separating any gas mixture (or purifying any gas component) over adsorbent which may be deactivated or otherwise degraded by contact with atmospheric humidity for air either introduced within the PSA unit as part of its process duty, or else just externally contacting the PSA unit.

Fig 6 shows a non-return valve 201 and a shutoff valve 202 deployed in series in product delivery conduit 147, so as to positively prevent back-migration of water from the product receiver or consumer when the PSA unit is shut down.

Fig. 6 further shows a light product storage vessel or surge chamber 203, which communicates with conduit 147 and which provides a volume of dry light product gas as shutdown purge gas for partial regeneration of the desiccant adsorber zone 3A upon depressurization and shutdown of the PSA unit. It is most desirable to keep the rotor or rotary valve turning during purge, so all adsorbers are purged equally. Vacuum pump 103 may be operated so as to increase the degree of regeneration of desiccant zone 3A that can be achieved with a finite volume of purge gas from receiver 203.

Fig. 6 also shows a auxiliary heater device 210 which is used to heat the desiccant adsorber zone 3A for enhanced regeneration during shutdown purging from surge chamber 203. Heater device 210 may generally use any technique for localized heating. Alternative suitable heater devices may be based on electrical resistance heaters embedded on adsorber zone 3A, or on infrared heat lamp radiation ntios, or microwave radiation. As some preferred embodiments of the adsorbent laminate use wire mesh screens or metal foils as the adsorbent sheet support, inductive eddy current heating is also a viable heater device approach within the invention. Localized heating may also achieved by increasing the load on rotary valve seals, or by operating the vacuum pump and/or compressor in a recirculation mode so as to heat at least the feed end of the adsorbers.

Fig. 1


1
14
12
16
4
106
131
176
181
21
11
175
178
125
5
6
9
113
121
10
3
3B
177
161
160
140
145
7
163
147
22
105
162
3A
8
12
132
117
126
172
170
182
26
27
28
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171
126
30
180
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13
17

Fig. 2

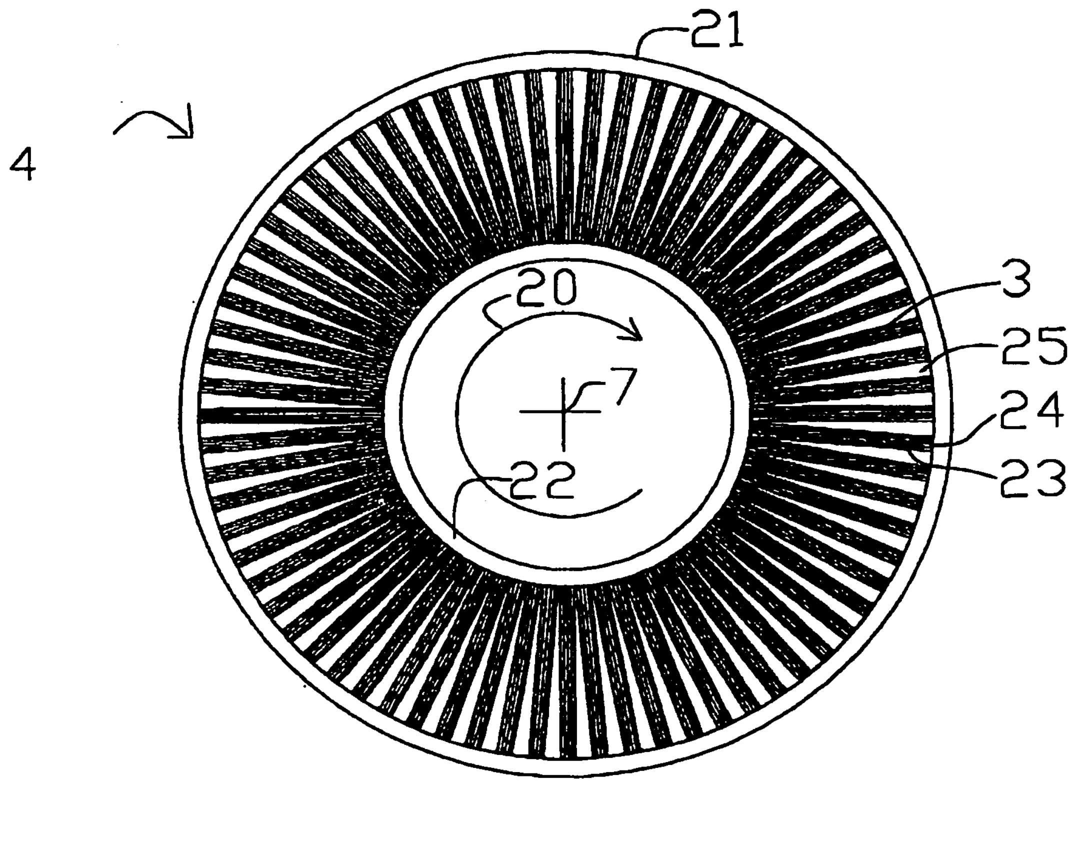


Fig. 3

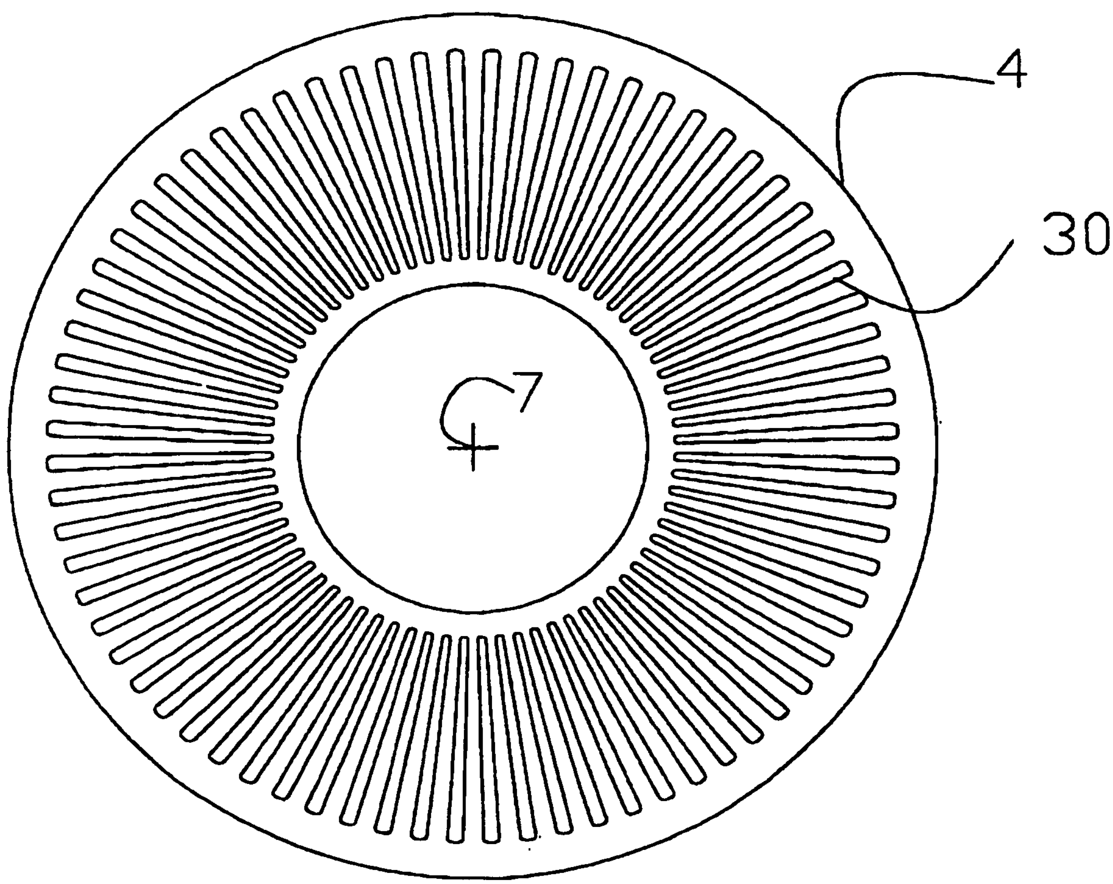
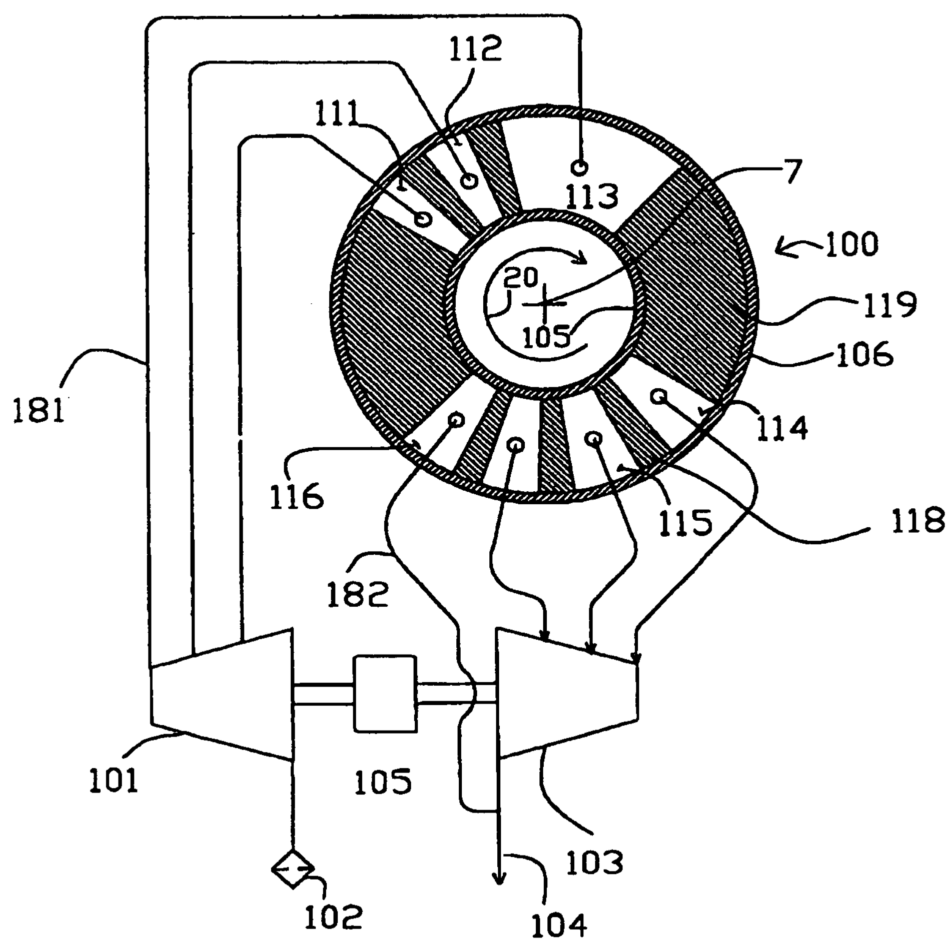


Fig. 4A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111
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181
114
116
115
118
182
101
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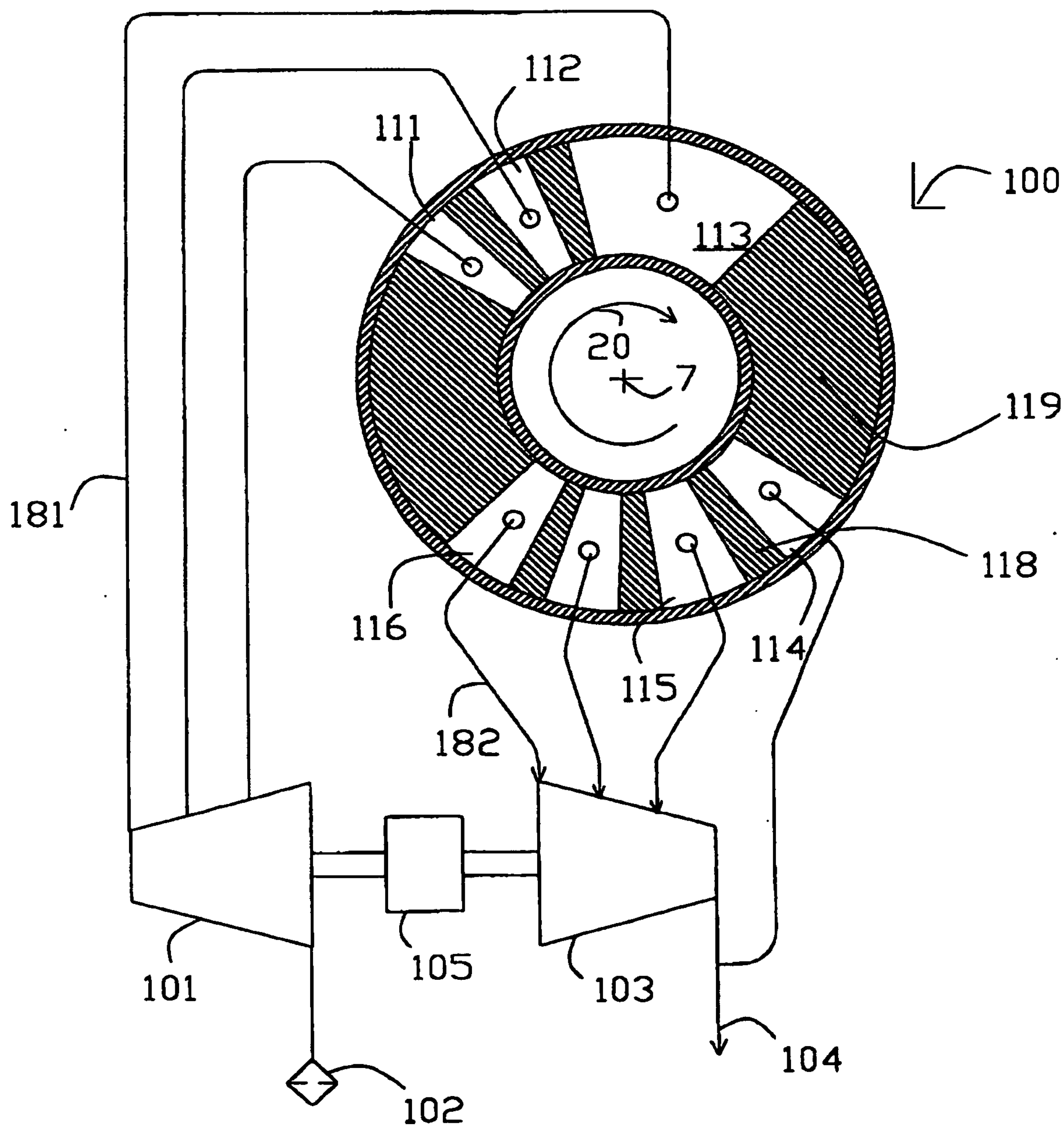
103
102
104

Fig. 4B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111
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182
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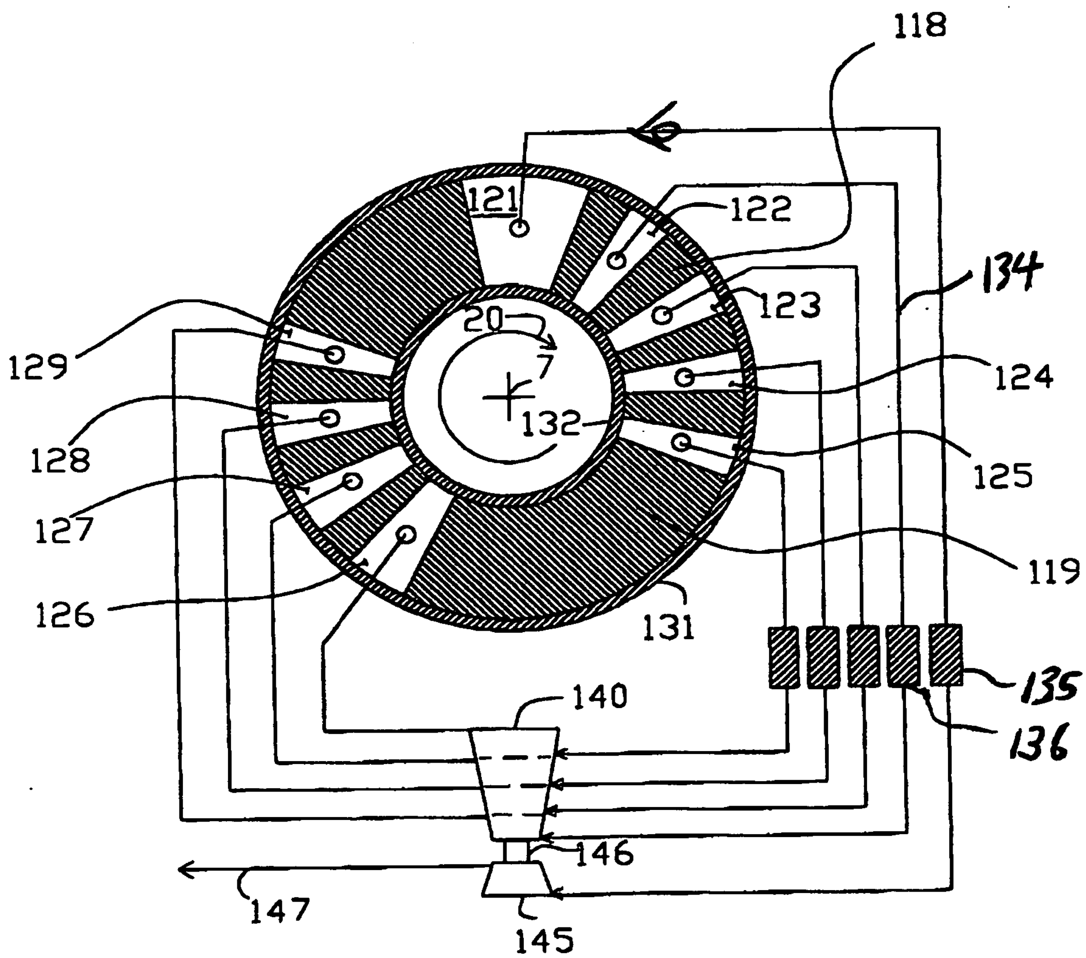
102

Fig. 5A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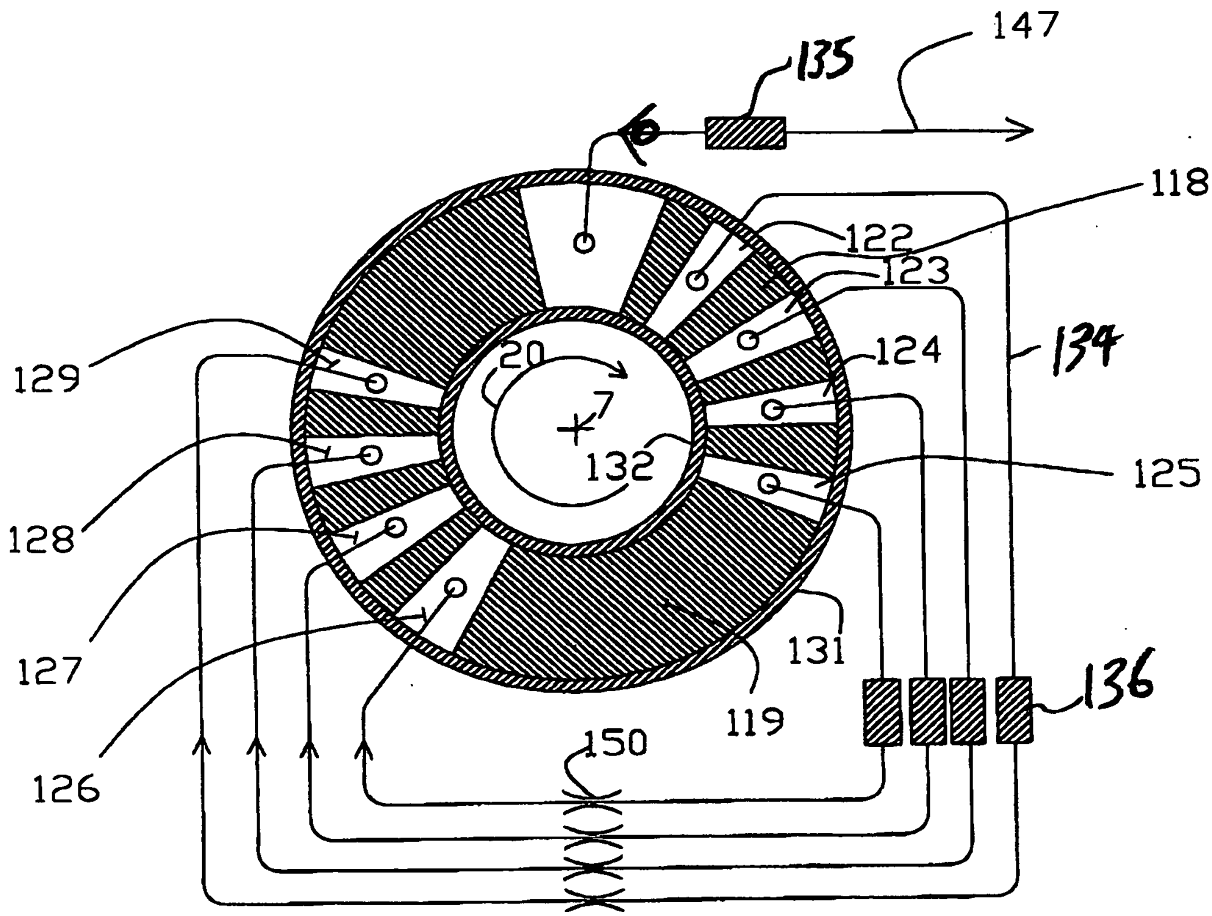
145

Fig. 5B


147
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134
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128
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131
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136
126
150

FIG. 6

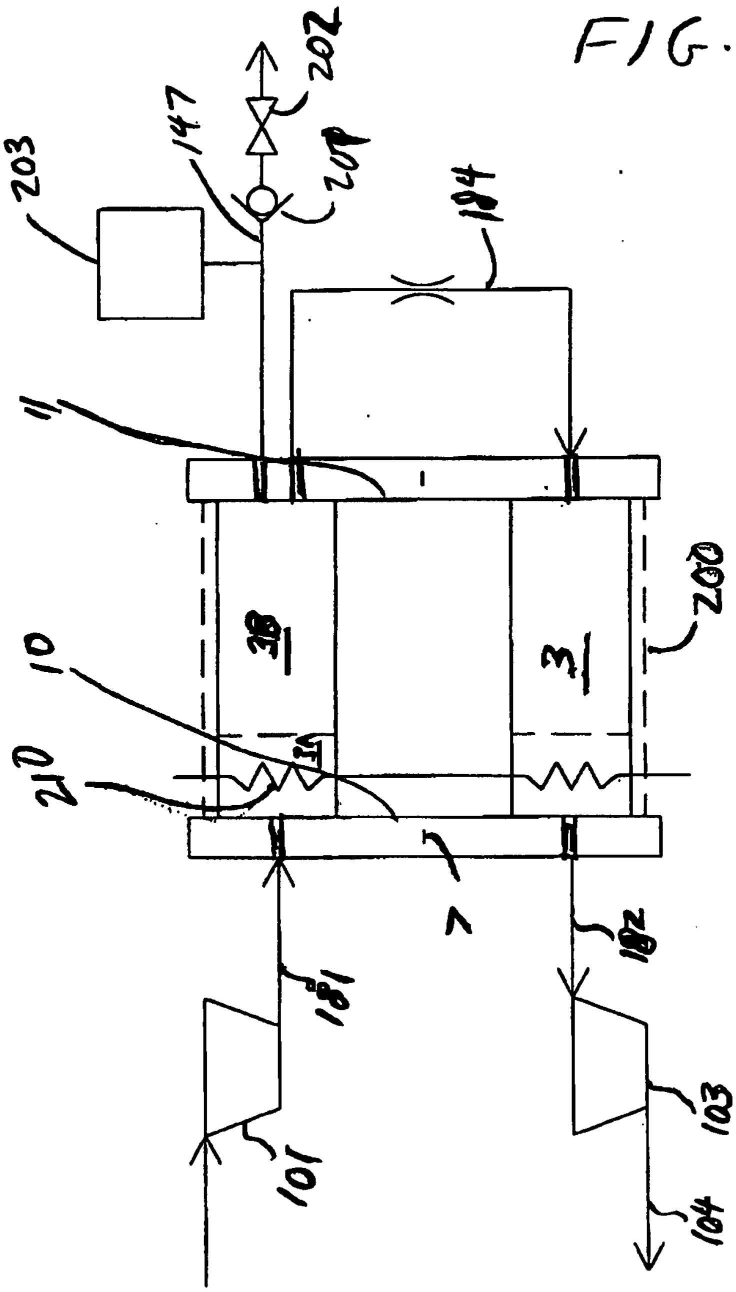


FIG. 7

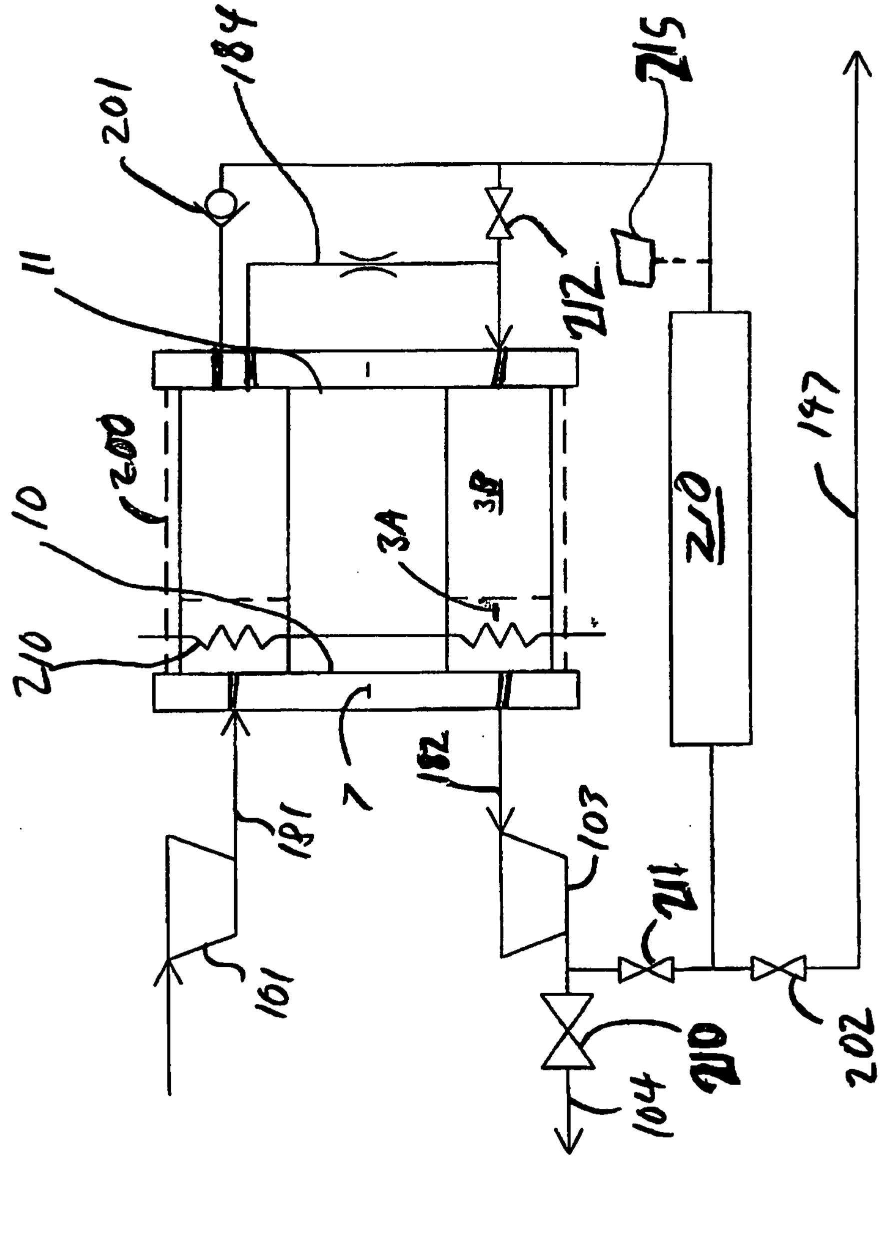

201
184
215
11
212
200
10
3A
3B
210
147
7
182
181
103
101
211
202
104

FIG. 8

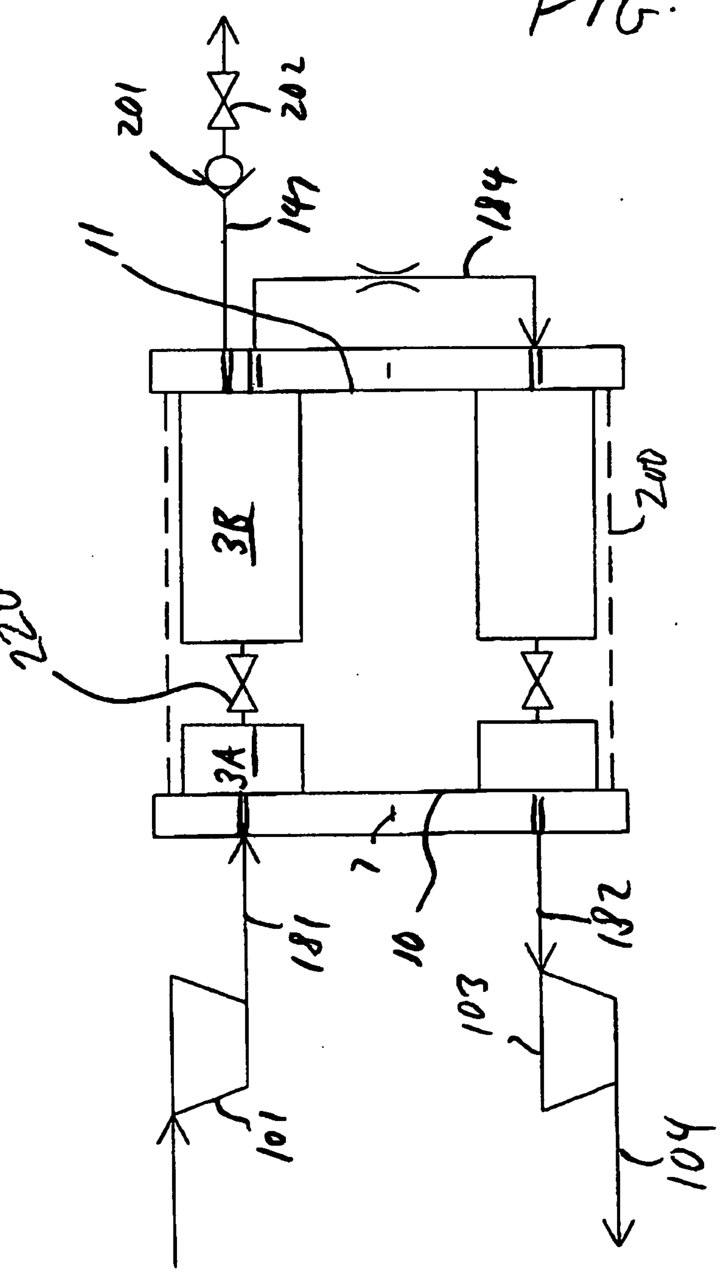


FIG. 9

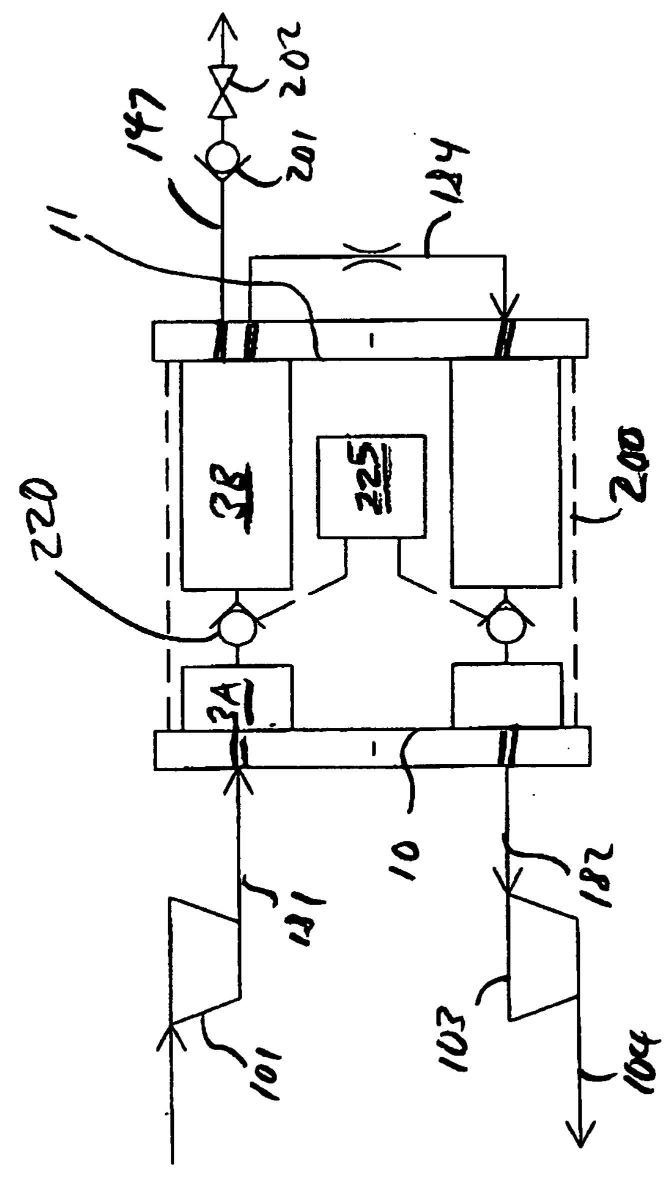


FIG. 10

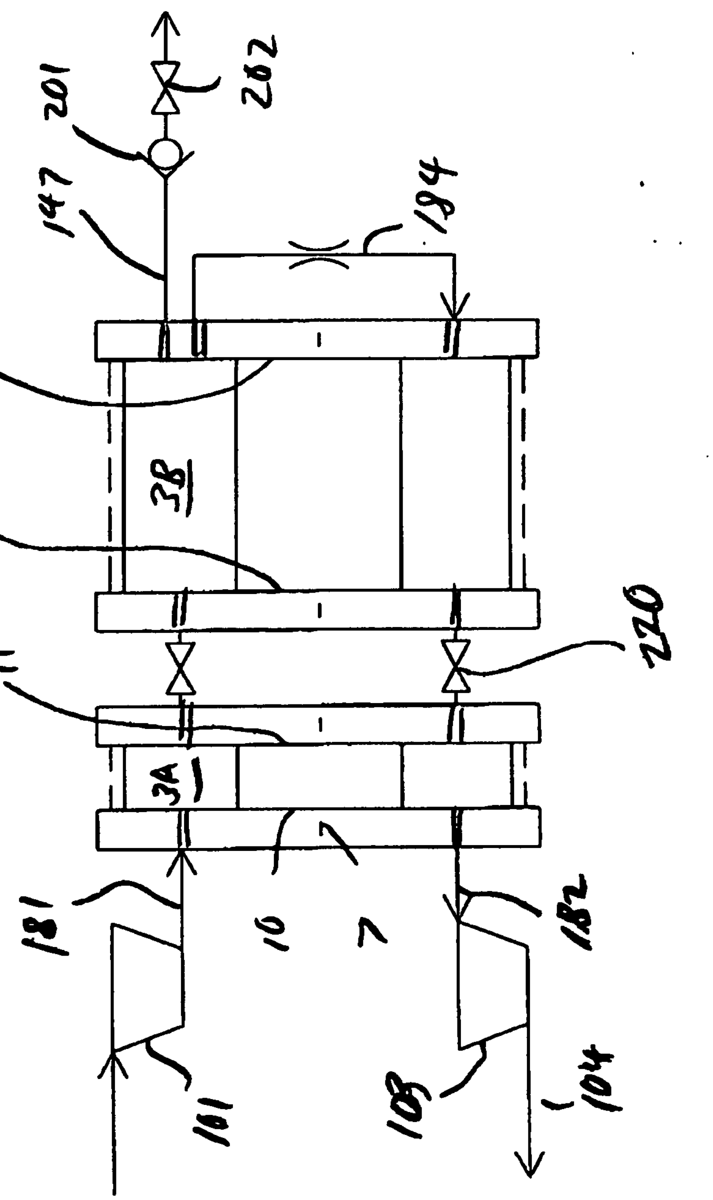


FIG. 11

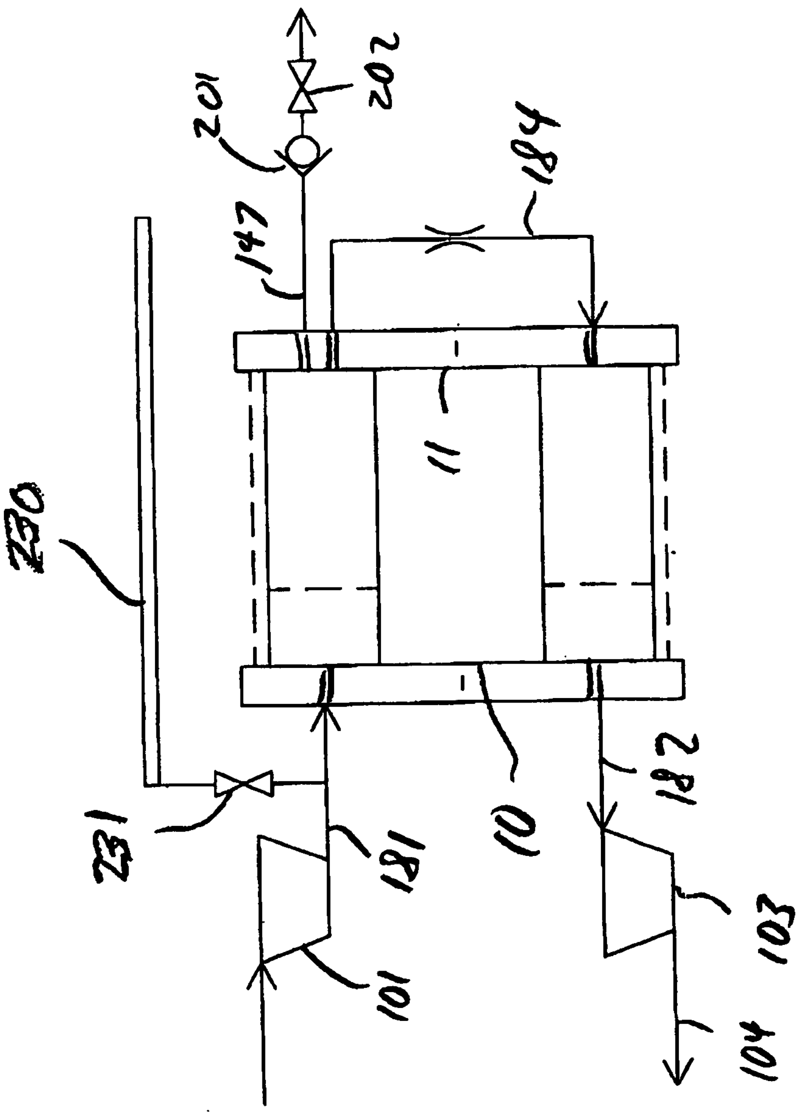


FIG. 12

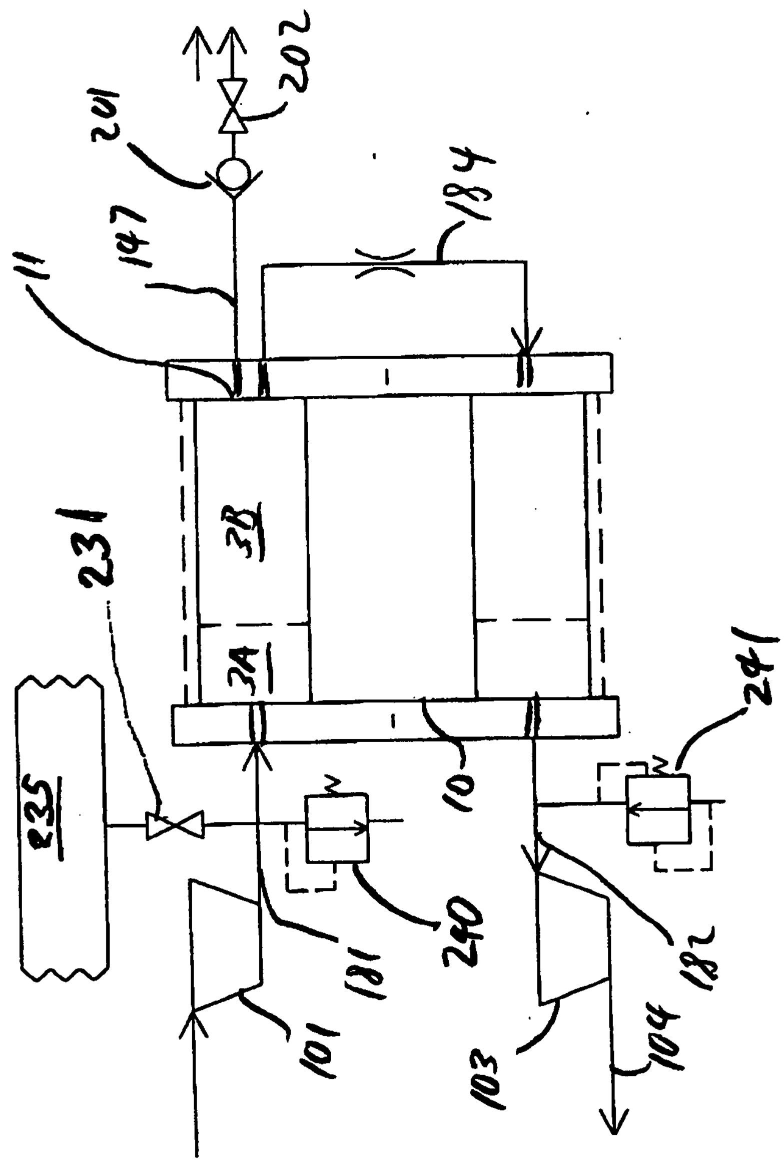


FIG. 13

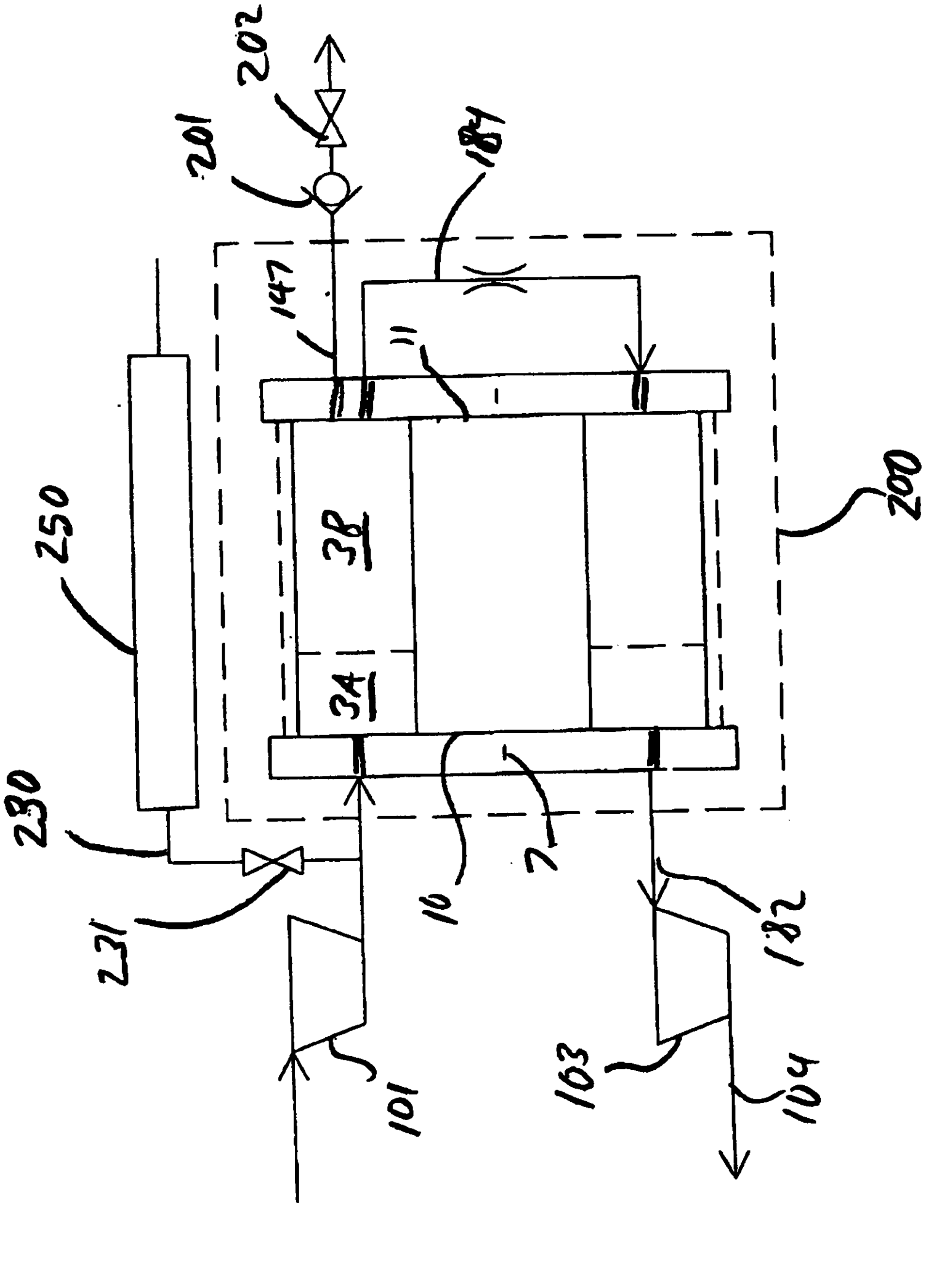


FIG. 14

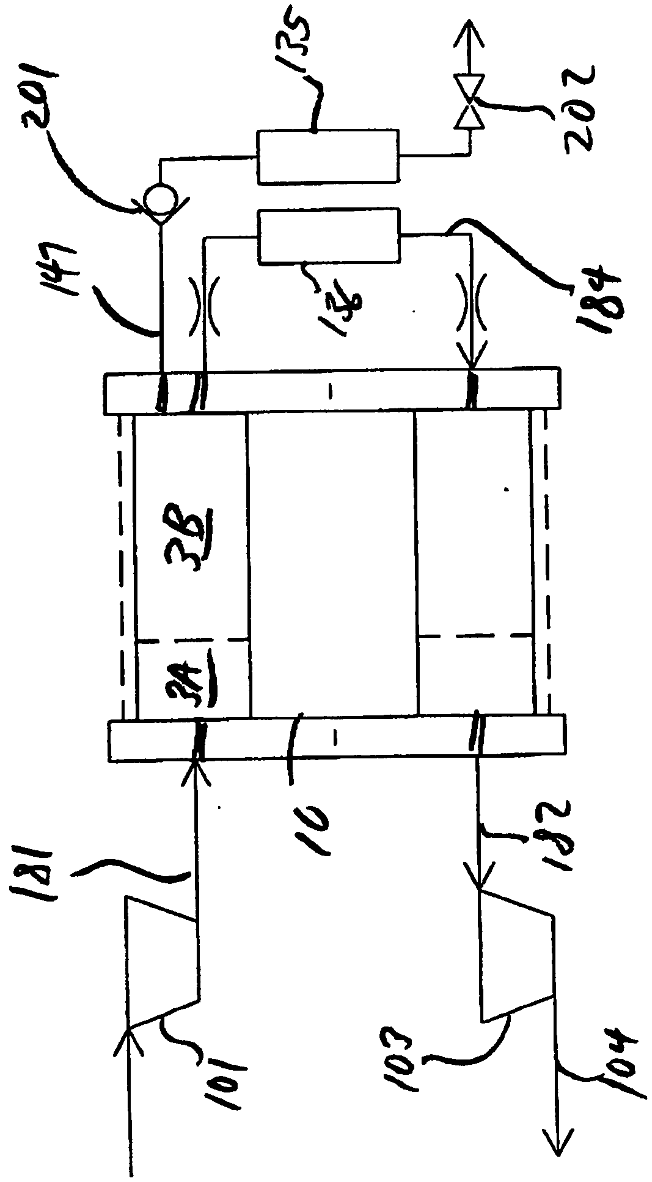
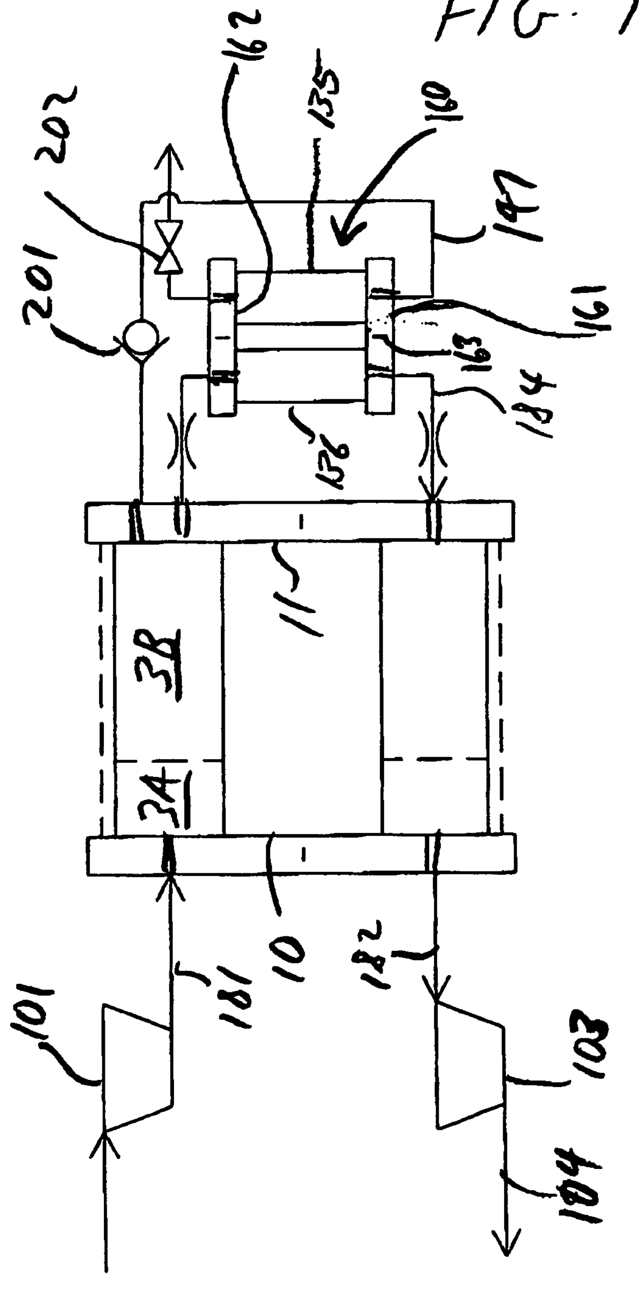


FIG. 15


162
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136
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3B
3A
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181
182
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103
104